Probing Primordial Gravitational Waves: Ali CMB Polarization Telescope Postprint

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Abstract

In this paper, we will give a general introduction to the project of Ali CMB Polarization Telescope (AliCPT), which is a Sino-US joint project led by the Institute of High Energy Physics (IHEP) and has involved many different institutes in China. It is the first ground-based cosmic microwave background (CMB) polarization experiment in China and an integral part of China' s Gravitational Waves Program. The main scientific goal of AliCPT project is to probe the primordial gravitational waves (PGWs) originated from the very early Universe.

The AliCPT project includes two stages. The first stage referred to as AliCPT-1, is to build a telescope in the Ali region of Tibet with an altitude of 5,250 meters. Once completed, it will be the world' s highest ground-based CMB observatory and open a new window for probing PGWs in the northern hemisphere. AliCPT-1 telescope is designed to have about 7,000 TES detectors at 90GHz and 150GHz. The second stage is to have a more sensitive telescope (AliCPT-2) with more than 20,000 detectors.

Our simulations show that AliCPT will improve the current constraint on the tensor-to-scalar ratio r by one order of magnitude with 3 years' observation. Besides the PGWs, the AliCPT will also enable a precise measurement on the CMB rotation angle and provide a precise test on the CPT symmetry. We show 3 years' observation will improve the current limit by two orders of magnitude.

Full Text

Preamble

Probing Primordial Gravitational Waves: Ali CMB Polarization Telescope

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In this paper, we provide a general introduction to the Ali CMB Polarization Telescope (AliCPT) project, a Sino-US joint initiative led by the Institute of High Energy Physics (IHEP) that involves numerous institutes across China. As China’ s first ground-based cosmic microwave background (CMB) polarization experiment and an integral part of China’ s Gravitational Waves Program, AliCPT’ s primary scientific goal is to probe primordial gravitational waves (PGWs) originating from the very early Universe.

The AliCPT project comprises two stages. The first stage, AliCPT-1, involves constructing a telescope at an altitude of 5,250 meters in the Ali region of Tibet. Upon completion, this will be the world’ s highest ground-based CMB observatory, opening a new window for PGW detection in the northern hemisphere. AliCPT-1 is designed to feature approximately 7,000 Transition Edge Sensor (TES) detectors operating at 90 GHz and 150 GHz. The second stage will deploy a more sensitive telescope (AliCPT-2) with over 20,000 detectors.

Our simulations demonstrate that AliCPT will improve current constraints on the tensor-to-scalar ratio r by one order of magnitude after three years of observation. Beyond PGWs, AliCPT will also enable precise measurement of the CMB rotation angle, providing a stringent test of CPT symmetry. We show that three years of observation will improve current limits by two orders of magnitude.

Introduction

The search for gravitational waves (GWs) has long been a cornerstone of cosmology and astrophysics since Einstein formulated General Relativity in the early 20th century. Gravitational waves represent the final untested prediction of general relativity. After sustained efforts, the LIGO (Laser Interferometer Gravitational-Wave Observatory) collaboration announced the first direct detection of GWs in 2016, with signals originating from two merging black holes of several tens of solar masses [**?**]. Since then, LIGO and Virgo have reported three additional black hole GW events [**?**]. These achievements ushered in a new era of GW astronomy and were recognized with the Nobel Prize in Physics.

Unlike the GWs detected by LIGO and Virgo, primordial gravitational waves arise from quantum fluctuations and carry crucial information about the very early Universe, including the physics of inflation, bouncing cosmologies, and emergent Universe scenarios. To date, the most effective method for probing PGWs is measuring the B-mode polarization of the CMB.

CMB photons are relic radiation from the Big Bang. Their first detection half a century ago pioneered the field of cosmology, and over the past two to three decades, rapid advances in CMB observations have brought us into the era of precision cosmology. However, the CMB B-mode polarization induced by tensor fluctuations generated in the early Universe—namely PGWs—has not yet been conclusively detected, making this a key scientific target for current CMB observations. Additionally, CMB B-modes provide important tests of fundamental physics, such as CPT symmetry. While the BICEP2 collaboration announced a B-mode detection in 2014, it was later attributed to dust emission rather than PGWs [**?**].

Currently, major ground-based CMB experiments are located in the southern hemisphere, including the Atacama Cosmology Telescope (ACT) and POLARBEAR/Simons Array in Chile, and the South Pole Telescope (SPT) and BICEP at the South Pole. High-precision experiments in the northern hemisphere are critically needed to achieve full sky coverage.

In 2014, the IHEP cosmology team proposed a CMB experiment in Ali, Tibet, to search for PGWs in the northern hemisphere. This paper provides a general introduction to the AliCPT project. Section II describes the atmospheric conditions, sky coverage, and infrastructure at the AliCPT site. Section III presents the primary scientific goals of AliCPT. Section IV offers a summary.

II. Overview of the AliCPT Site

Ali prefecture lies in the western Tibetan Plateau, characterized by vast highlands. The AliCPT site is situated atop a peak in the northwestern Gangdise mountain range, which features numerous peaks exceeding 5,000 and even 6,000 meters. The Xinjiang-Tibet Highway (officially China National Highway 219) and Ngari Gunsa Airport are located nearby.

This section describes the atmospheric conditions, sky coverage, and infrastructure at the AliCPT site—critical factors for ground-based CMB experiments. Atmospheric conditions are paramount for ground-based CMB telescopes, as atmospheric absorption and emission at millimeter and sub-millimeter wavelengths degrade signal significance. Among atmospheric constituents, water vapor is particularly problematic due to its strong absorption/emission properties and high temporal variability. Precipitable Water Vapor (PWV), defined as the total depth of water in a column of atmosphere above the ground, serves as the standard parameter for characterizing water vapor content. Since CMB signals, especially polarization signals, are extremely faint, observations require thin, dry, and stable atmospheric conditions.

The upper panel of Figure 1 [Figure 1: see original paper] shows the global distribution of mean PWV values over the past six years (2011.7-2017.7). Only four regions exhibit the lowest PWV on Earth: Antarctica, the Atacama Desert, Greenland, and the high Tibetan Plateau. The AliCPT site, located at 5,250 meters on the Gangdise Mountain, benefits from the Himalayas to its southwest, which run from northwest to southeast and separate the Ali region from the Indian subcontinent and Indian Ocean, as shown in the lower panel of Figure 1. This topography significantly reduces moist air from the Indian Ocean, making the AliCPT site sufficiently thin and dry during winter.

In [**?**], we quantitatively analyzed the site' s atmospheric conditions using radiosonde data from the local weather station and MERRA-2 reanalysis data from NASA/GMAO. The results reveal strong seasonal PWV variation in Ali, with a median PWV of approximately 1 mm during the observing season (October to March)—1.07 mm from MERRA-2 and 0.92 mm from radiosondes—excellent for observations at 90/150 GHz. Figure 2 [Figure 2: see original paper] shows the cumulative fraction of time versus PWV. Additional atmospheric evaluations for the Ali region appear in [**?**].

Regarding sky coverage, the AliCPT site is located at geographic coordinates (80°01 E, 32°19 N). Due to Earth' s rotation and its mid-latitude position, AliCPT can observe the entire northern sky and the low-latitude portion of the southern sky, achieving an overall observable fraction of approximately 70 percent, as shown in Figure 3 [Figure 3: see original paper] (region above the black dashed line). Our calculations assume instrumental parameters of 45° minimum elevation for the mount and 30° field of view (FOV). The overlap in low-latitude observable sky between Ali and Atacama facilitates cross-check and cross-correlation studies. The "northern hole" —the region of lowest foreground contamination in the northern galactic hemisphere—falls within AliCPT' s observable sky, which is crucial for a CMB B-mode polarization and PGW project. Figure 3 shows AliCPT' s target fields: TN1 and TN2 within the black solid lines in the northern galactic hemisphere, and TS in the southern galactic hemisphere. TND, with the lowest dust intensity, is selected for deeper survey.

Thus, AliCPT' s sky coverage—both in terms of observable area and low foreground contamination—complements experiments in Antarctica and Atacama.

Combined with the cleanest southern sky regions covered by projects such as BICEP and Simons Array, AliCPT increases the probability of detecting B-modes and PGWs. Further sky coverage details are available in [**?**].

Infrastructure at the site is well-developed. The National Highway 219 runs adjacent to the AliCPT site, and Ngari Gunsa Airport is only about a half-hour drive away, offering daily commercial flights to Lhasa, Tibet' s capital. Shiquanhe town, the largest settlement in the Ali area, is also nearby, just a 30-minute drive from the site.

An aerial view around the Ali Astronomical Observatory at point A1 (left panel of Figure 4 [Figure 4: see original paper]) shows that the AliCPT site at B1 is only about 1 km from A1. The concrete road from A1 to B1 is under construction and nearing completion. At the Ali Astronomical Observatory (point A1), city grid electricity and network infrastructure for data transmission are already operational, and several optical telescopes for astrophysics have been installed. Site construction for AliCPT began in March 2017 and will be completed by the end of this year. After commissioning in 2019, observations are expected to commence in 2020.

In summary, AliCPT opens a new window in the northern hemisphere for detecting CMB B-mode polarization and probing PGWs.

III. AliCPT and Its Scientific Goals

This section introduces the AliCPT project components and presents simulations of its scientific goals. The AliCPT project consists of two stages. The first stage involves developing and deploying a CMB polarization telescope at 5,250 meters, designated AliCPT-1. AliCPT-1 is a dichroic refractor with a 70 cm aperture covering 90/150 GHz, featuring a three-axis mount scanning at 5°/s in azimuth. AliCPT-1 employs Transition Edge Sensor (TES) bolometers widely used in current CMB polarization experiments [**?**], with Superconducting Quantum Interference Devices (SQUIDs) as cryogenic readout. Sensors and readout electronics are packaged into highly integrated modules, each containing 1,704 TES sensors. Four modules will be installed in AliCPT-1 by the end of 2019, yielding 6,816 detectors.

The second stage will deploy a more sensitive telescope (AliCPT-2) with 12 modules and over 20,000 detectors. Construction of AliCPT-2 will begin in 2020, with four modules installed annually to complete all 12 modules by the end of 2022. Table I [TABLE:N] summarizes the basic instrumental parameters used for simulations and the deployment schedule for AliCPT-1 and AliCPT-2.

The primary scientific goals of AliCPT include: conducting large-coverage surveys in the northern hemisphere to identify low foreground contamination regions; targeting the cleanest sky regions to detect PGWs in the northern hemisphere; measuring the CMB rotation angle with high precision to test CPT symmetry; studying hemispherical asymmetry in combination with southern hemisphere experiments; measuring E-mode polarization with high precision to study cosmological effects; and investigating cross-correlations between CMB polarization and large-scale structures (LSS).

Below, we present simulations of the measurement sensitivity for r and the CMB rotation angle.

A. Sensitivity on r and Its Implication for Early Universe Physics

The leading paradigm for the early Universe is inflationary cosmology, which describes an accelerated expansion phase preceding the radiation-dominated epoch. Inflation resolves several conceptual problems of Big Bang theory, including the flatness, monopole, and horizon issues [**?**]. Moreover, inflation explains the origin of primordial perturbations through a mechanism whereby quantum fluctuations of the inflaton field were stretched into classical perturbations by the exponential spatial expansion. Primordial perturbations consist of three types: scalar, vector, and tensor. Scalar modes seed CMB temperature anisotropies and lead to large-scale structure formation, while tensor modes–known as PGWs –produce CMB B-mode polarization, the target signal for AliCPT observations. Conventionally, tensor perturbations are described by parameters such as r and n , where r represents the ratio of primordial tensor power spectrum amplitude (A) to scalar amplitude (A), and n denotes the tensor spectral index defined as the logarithmic derivative: $n \quad d \ln P \, / \, d \ln k$, where P is the tensor mode power spectrum and k is the wavenumber.

Since inflationary cosmology still faces the initial singularity problem [**?**], alternative theoretical approaches have been proposed, including bounce cosmology [**?**], cyclic Universe [**?**], and emergent Universe [**?**]. Like inflation, these theories can generate primordial tensor perturbations, but PGWs from different theories exhibit distinct characteristics reflected in the shape of the CMB BB spectrum. Figure 5 [Figure 5: see original paper] compares typical model predictions for the r–n relationship with current and forthcoming CMB experiments [**?**], demonstrating that high-precision PGW measurements are crucial for testing early Universe models.

We have performed simulations to forecast AliCPT' s constraining power. To derive constraints on r from AliCPT observations, we employ the Fisher matrix approach [**?**], an efficient method for forecasting parameter constraints given instrument specifications. For multivariate Gaussian-distributed data vector $\mathbf{d}$, the likelihood function is:

$$\mathcal{L}(\mathbf{d}|\theta) = \frac{1}{\sqrt{|C(\theta)|}} \exp\left(-\frac{1}{2}\mathbf{d}^{\dagger}[C(\theta)]^{-1}\mathbf{d}\right)$$

where θ is the parameter vector and C is the covariance matrix (generally a function of θ). The Fisher matrix F_{ij}, defined as the second partial derivative of the log-likelihood with respect to parameters θ_i and θ_j evaluated at the fiducial model, approximates the Hessian matrix. The inverse of diagonal elements $(F^{-1})_{ii}$ provides an estimate of the lower limit on variance for parameter θ_i, i.e., $\Delta\theta_i \geq (F^{-1})_{ii}^{1/2}$.

For CMB observations, $\mathbf{d} = \{X_{\nu,\ell m}, ...\}$, where $X \in \{T, E, B\}$ and ν runs over all frequency bands. Each ℓm mode contains three components: lensed CMB, foreground emission, and instrumental noise. The Fisher matrix for CMB observables is:

$$F_{ij} = \sum_{\ell} \frac{2\ell+1}{2} f_{\text{sky}} \text{Tr}\left[\frac{\partial C_\ell}{\partial \theta_i} C_\ell^{-1} \frac{\partial C_\ell}{\partial \theta_j} C_\ell^{-1}\right]$$

where ℓ denotes multipole order, f_{sky} is sky coverage, and C_ℓ is the harmonic-space covariance matrix:

$$C_\ell(X^\mu_{\ell m}, Y^\nu_{\ell m}) = C_\ell^{XY,\mu\nu} + F_\ell^{XY,\mu\nu} + N_\ell^{XY,\mu\nu}$$

with C_ℓ, F_ℓ, and N_ℓ representing spectra of lensed CMB, foreground, and instrumental noise, respectively. We assume statistically isotropic temperature and polarization fields, making different ℓ modes independent.

We use CAMB [**?**] to compute CMB spectra C_ℓ, adopting a fiducial cosmology consistent with Planck 2015 results [**?**]. Theoretically, the lensing B-mode signal exceeds the primordial signal at the recombination bump ($\ell \sim 100$) when r falls below 0.01. Therefore, to achieve high-precision detection of primordial B-modes, we must perform delensing to remove lensing effects from the data. Our simulations consider two cases for comparison: fully delensed and undelensed. During operations, we will reconstruct lensing spectra using AliCPT data and other small-scale CMB surveys at high ℓ, with alternative approaches such as cross-correlating CMB with large-scale structure surveys also under consideration.

Based on recent experimental results, foreground emission F_ℓ dominates across all frequency bands and angular scales. This contamination can be removed through multi-frequency observations since CMB and foreground components have distinct frequency spectra. Component separation methods estimate the contribution of each emission component, though some residual foreground inevitably remains after processing. AliCPT plans to survey the cleanest sky regions at 90/150 GHz to minimize residual foreground contamination. In our Fisher forecasts, we consider two foreground components: synchrotron and thermal dust, which dominate polarized foreground emission. Besides r, we include six additional free parameters: A_{dust} and A_{sync} (amplitudes of dust and synchrotron at $\ell = 80$ with pivot frequencies 353 GHz and 23 GHz), α_{dust} and α_{sync} (spectral indices in harmonic space), and β_{dust} and β_{sync} (spectral indices in frequency space). We assume no correlation between dust and synchrotron components.

For instrumental noise, we assume uncorrelated temperature and polarization noise with an isotropic Gaussian random distribution. The temperature noise spectrum is:

$$N_\ell = w^{-1} B_\ell^2$$

where B_ℓ is the harmonic transform of the Gaussian beam:

$$B_\ell = \exp\left[-\ell(\ell+1)\theta_{\mathrm{FWHM}}^2/8\ln 2\right]$$

and the noise weight is:

$$w^{-1} = \frac{4\pi f_{\mathrm{sky}} \mathrm{NET}^2}{t_{\mathrm{obs}} N_{\mathrm{det}}}$$

where NET is Noise Equivalent Temperature (dependent on detector performance, instrument design, and atmospheric conditions), t_{obs} is effective observation time (October to March, 10 hours per day), and N_{det} is the number of detectors. For polarization, NET is multiplied by $\sqrt{2}$ since each polarized signal requires two orthogonal linear polarized detectors. Table I lists the instrumental parameters used in our calculations.

Figure 6 [Figure 6: see original paper] presents our results, showing simulated r sensitivity for undelensed (left panel) and fully delensed (right panel) cases. Both panels consider residual foreground levels of 1%, 5%, and 10%. The horizontal black dashed line indicates the current limit $r < 0.07$. Even in the undelensed case with 10% residual foreground, three years of AliCPT survey yield sensitivity $\sigma_r = 0.007$, nearly one order of magnitude stronger than current constraints. By the end of 2025, after three years of observation with 16 detector modules (approximately 27,000 TES detectors), the delensed constraint on r will reach 0.003. Unsurprisingly, lower residual foreground improves r constraints; suppressing foregrounds to the 1% level with delensing yields $\sigma_r \sim 0.001$. Such stringent limits on r will enable testing of numerous early Universe cosmological models, providing new insights into this epoch.

B. Sensitivity on the CMB Polarization Rotation Angle and Its Implication for CPT Tests

Testing CPT symmetry—the combination of charge conjugation (C), parity reflection (P), and time reversal (T)—is crucial for cosmology and particle physics. Any detected violation would provide powerful evidence for physics beyond the Standard Model. While laboratory experiments consistently show null results for CPT violation, these tests may not apply to extremely high-energy processes in the early Universe. Indeed, cosmological motivations exist for considering CPT violation: the expanding Universe possesses a preferred temporal direction that naturally breaks Lorentz and CPT symmetries, and the observed baryon-antibaryon asymmetry may indicate dynamical CPT violation [?].

To study cosmological CPT violation in the CMB, we consider the effective Lagrangian:

$$\mathcal{L}_{\mathrm{CS}} = p_\mu A_\nu \tilde{F}^{\mu\nu}$$

where the external field p_μ may be a constant vector [?], or $p_\mu \sim \partial_\mu \phi$ with ϕ a dark energy scalar in quintessential baryo/leptogenesis [?], or $p_\mu \sim \partial_\mu R$ with R the Ricci scalar in gravitational baryo/leptogenesis [?], and $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ is the dual electromagnetic tensor. The Chern-Simons term rotates photon polarization directions for CMB photons, converting some E-mode polarization to B-mode and altering polarization power spectra [?]. Table II [TABLE:N] summarizes constraints on the rotation angle from various experiments; the current limit on the rotation angle α is approximately 1°.

We have performed simulations to forecast AliCPT' s sensitivity to the rotation angle measurement. For this forecast, we employ D-estimators [?] defined as:

$$D_\ell^{\mathrm{TB,obs}} = C_\ell^{\mathrm{TB,obs}} \cos(2\beta) - C_\ell^{\mathrm{TE,obs}} \sin(2\beta)$$

$$D_\ell^{\mathrm{EB,obs}} = C_\ell^{\mathrm{EB,obs}} \cos(4\beta) - \frac{1}{2}(C_\ell^{\mathrm{EE,obs}} - C_\ell^{\mathrm{BB,obs}}) \sin(4\beta)$$

where β is the unbiased estimator for the cosmic rotation angle α.

We modified the generic Monte Carlo Markov Chain (MCMC) sampler in the CosmoMC package [?] and performed calculations using AliCPT' s instrumental properties. Figure 7 [Figure 7: see original paper] presents our results, with blue dashed and black solid lines showing constraints from TB and TB+EB estimators, respectively. After three years of observation, AliCPT can achieve a stringent constraint on the average rotation angle of $\sigma(\alpha) \sim 0.01°$.

IV. Summary

This paper has introduced the AliCPT project and its scientific goals. Upon completion, AliCPT will join Chile and the South Pole as one of the world' s major CMB polarization observatories, enabling full-sky coverage in the search for PGWs.

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